# E-GRIP: A Highly Elliptical Orbit Satellite Mission for Co-location in Space

Benjamin Männel[1], Markus Rothacher[1], Philippe Jetzer[2], Steve Lecomte[3], Pascal Rochat[4]

**Abstract** The Einstein Gravitational Red-shift Probe (E-GRIP) will be a new satellite mission allowing detailed studies for relativistic and geodetic purposes. The scientific objectives of E-GRIP are the measurement of the space-time curvature around the Earth, multiple tests of general relativity, and special geodetic applications. E-GRIP will fly in a highly eccentric orbit ($e > 0.6$, apogee $> 35000$ km) and will carry a narrow- and a wide-angle microwave link (at both X- and K-band), two GNSS antennas, SLR retro-reflectors, a photon counter unit, and a space hydrogen maser. Consequently, E-GRIP could act as a co-location satellite with suitable observation conditions for VLBI. Beyond a mission overview, we provide results from extended VLBI simulations concerning link budget, visibilities, and achievable station coordinate results. In addition, we present also some basic considerations concerning the feasibility of co-located GNSS and SLR observations for E-GRIP's highly elliptical orbit.

**Keywords** VLBI, E-GRIP, co-location, satellite-tracking

## 1 Introduction

In recent years much effort has been undertaken to combine space geodetic observations on-board satellites, known as co-location in space. Whereas co-locations on-board Low Earth Orbiters (LEO) and on-board GNSS satellites already exist for SLR and GNSS, no such satellites are allowing at present for VLBI observations. In order to cure this situation new satellite missions such as JPL/CNES's Geodetic Reference Antenna in Space (GRASP, Bar-Sever et al., 2009) are considered, new observation concepts such as tracking of GNSS L-band signals were implemented (e.g. Tornatore et al., 2014; Haas et al., 2014), and at some telescopes, receiver chains were modified (Kodet et al., 2014). Evaluating today's situation, three possibilities for a near-future co-location satellite are feasible: a dedicated LEO mission, GNSS satellites, and a dedicated satellite in a highly elliptical orbit. Table 1 lists the main advantages/disadvantages concerning the VLBI tracking for each of these possibilities. According to Table 1, a LEO is an easy way to implement a dedicated co-location satellite due to the low costs regarding launch and spacecraft bus. However, as the low altitude limits the VLBI observability, elliptical orbits become interesting. When speaking of highly elliptical orbits within this paper, an eccentricity $e > 0.3$ is assumed. The advantage of such an orbit is obvious: due to the high altitude close to the apogee, VLBI tracking with long baselines becomes possible, and, as the apparent satellite speed is slow, no requirements on the slew rates have to be fulfilled. However, three major concerns have to be addressed (1) VLBI tracking close to the perigee might be as challenging as it is for LEOs, (2) GNSS and SLR observations are challenging during apogee crossings, and (3) the tracking statistics will be inhomogeneous due to the orbit geometry. Within this paper we introduce E-GRIP as a highly elliptical orbit mission including a description of the planned microwave link

1. ETH Zürich, Switzerland
2. University of Zürich, Switzerland
3. Centre Suisse d'Electronique et de Microtechnique, Neuchâtel, Switzerland
4. Spectratime, Neuchâtel, Switzerland

**Table 1** Comparison of different satellite/orbit types for co-location in space concerning VLBI satellite tracking.

| | (near-circular) LEO | GNSS satellite | satellite in a highly elliptical orbit |
|---|---|---|---|
| space segment | low costs | already existing | costs are higher than for LEO |
| scheduling aspects | short baselines, short and fast passes require high slew rates | long passes, switching between spacecraft for better sky coverage | up to max. baseline length, very long and slow passes exist |
| observed signals | mission-dep. (S-,X-,K-Band) | L-Band | mission-dep. (S-,X-,K-Band) |
| coordinate results | ≈1 cm (Plank et al., 2014) for single-satellite tracking | 2-10 cm for single-satellite tracking, <1 cm for constellation tracking | 1-2 cm single-satellite tracking (during apogee) |
| conclusion | challenging due to short baselines and short passes | limitation due to L-Band signals | challenging for stations observing the perigee region |

(Section 2). In Section 3 we present results of our VLBI satellite tracking simulation studies for E-GRIP.

## 2 E-GRIP: Mission and Status

E-GRIP is a joint mission study of ETH Zürich, University of Zürich, Centre Suisse d'Electronique et de Microtechnique, and Spectratime. Currently E-GRIP is within an extended Phase 0/A, which will be finished in June 2016. E-GRIP has three major scientific objectives:

- testing of the local position invariance (i.e. testing Earth, Sun, and Lunar gravitational red-shift),
- tests of higher-order effects such as the Schwarzschild space curvature, the Shapiro time delay, and frame dragging, and
- tests of special geodetic applications:
  - inter/continental time comparison,
  - relativistic geodesy, and
  - co-location in space.

In order to perform these tasks E-GRIP will fly in a highly elliptical orbit. For our initial studies we selected two orbits:

- **EGRIP-A:** a = 24450 km, e = 0.636, $d_p$ = 2540 km
- **EGRIP-B:** a = 35000 km, e = 0.800, $d_p$ = 700 km.

The core of E-GRIP's scientific payload is an active space hydrogen maser stable to $1 \cdot 10^{-15}$@10000 s. This on-board time and frequency standard is connected to two microwave communication antennas which will be described later. Also one high-quality space-proofed GNSS receiver will be part of the payload. This receiver will be connected to a nadir- and a zenith-facing antenna allowing GNSS observations during apogee and perigee crossings. For SLR a retro-reflector array and a photon counting unit will be part of the payload.

The microwave link required for the ground-to-space clock comparison will allow the VLBI tracking of E-GRIP. In order to have a stable link during the entire revolution two antennas—one narrow-beam high-gain antenna (antenna 1) and one wide-beam low-gain antenna (antenna 2)—have been selected. Table 2 provides the characteristics of both antennas. Figure 1 shows an estimation of the received power for the microwave links listed in Table 2 depending on the orbit altitude. The minimal received power is $-125$ dBW and $-136$ dBW for an altitude of 20000 km and 50000 km, respectively. For comparison, -114 dBW can be received, when observing GNSS $L_1$ signals (Tornatore and Haas, 2009). Two conclusions can be drawn from Figure 1: (1) the signal loss due to

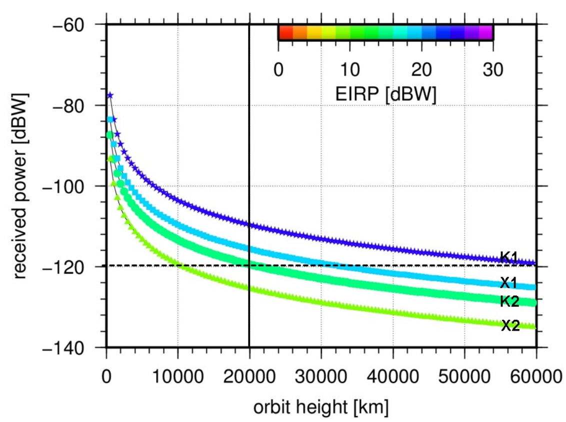
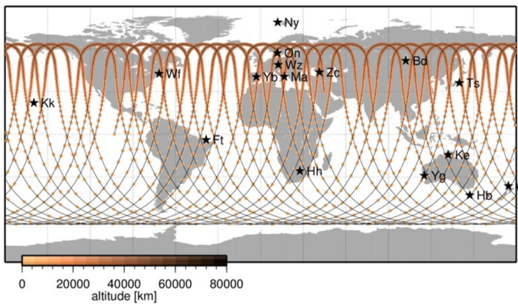
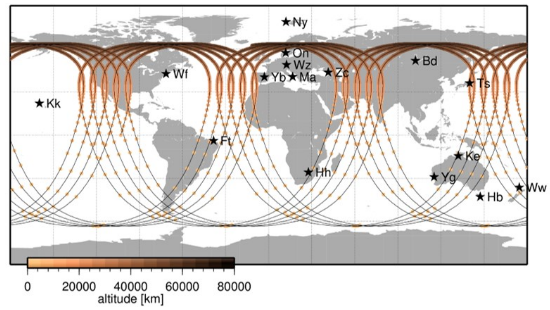



**Fig. 1** Link budget for the two microwave links (K1, X1 = antenna 1; K2, X2 = antenna 2).




(a) EGRIP-A orbit.




(b) EGRIP-B orbit.

**Fig. 2** E-GRIP ground tracks; GLOBAL station network; time period January 4 – January 18, 2015.

**Table 2** E-GRIPs antenna and microwave link characteristics.

| Ant. | working area | beam-width | frequency [GHz] | gain [dBi] |
|---|---|---|---|---|
| 1 | >20000 km | ±13.6° | K0: 22.96 ± 0.25 | >15.9 |
| | | | K1: 25.69 ± 0.25 | >15.9 |
| | | | X2: 8.458 ± 0.10 | >15.9 |
| 2 | <20000 km | ±42° | K0: 22.96 ± 0.25 | >6.1 |
| | | | K2: 25.69 ± 0.25 | >6.1 |
| | | | X2: 8.458 ± 0.10 | >6.1 |

the larger distance is not critical and (2) the received signals are still strong compared to quasar signals.

Looking at the considered apogee heights, it is obvious that GNSS and SLR observations are challenging for E-GRIP. Within two studies we addressed this topic and found that (1) by carrying a zenith- and a nadir-facing GNSS antenna, a minimum number of four GPS and GLONASS satellites is observable for nearly each epoch (max. nadir angle 23°) and (2) by carrying a retro-reflector array, SLR observations are challenging but possible over the entire arc.

## 3 Satellite Tracking Simulation

The simulations presented here were performed using a modified version of the Bernese GNSS Software (5.2) able to simulate and process VLBI satellite tracking data (Männel et al., 2014). For the simulation procedure we followed the IVS guidelines (Böhm et al., 2006), i.e., tropospheric wet zenith delays were generated using a turbulence model, and receiver clock errors were produced with a random walk and an integrated random walk process. Additionally, a white noise of 42 ps (≈1.4 cm) was applied to each observation (one observation per minute). We selected two station networks, one regional (EUROPE, 1) and one global (GLOBAL, 2):

- **EUROPE**: Matera, Metsähovi, Ny-Ålesund, Onsala, Svetloe, Wettzell, Yebes, and Zelenchukskaya
- **GLOBAL**: Badary, Fortleza, Hartebeesthoek, Hobart (both telescopes), Katherine, Matera, Ny-Ålesund, Onsala, Tsukuba, Warkworth, Westford, Wettzell, Yarragadee, Yebes, and Zelenchukskaya.

Figure 2 shows the ground tracks of the E-GRIP orbits including the GLOBAL station network.

In the first step we considered the visibility conditions for the individual satellite orbits. Figure 3 shows the number of epochs per week for which different satellites (LEO, GPS, EGRIP-A, EGRIP-B) are above the horizon for the individual stations. Additionally, also elevation cutoffs at 10° and 20° were considered. Obviously, for circular orbits the number of epochs will nearly be equal for all stations. Consequently, about the same number of epochs can be found for LEO and GPS satellite tracking. In the case of E-GRIP, the northern stations have significantly more observations than those in southern regions. This is explained by the orbit geometry, especially by the location of the apogee which is above the northern hemisphere (see Figure 2). To quantify the results shown in Figure 3, one can say that LEO is observable in 10% of all epochs and a GPS satellite in 40% of all epochs (cutoff = 0°). For the highly elliptical orbits these numbers range from 80 to 10% and from 90 to 2.5% for EGRIP-A and EGRIP-B, respectively. However, we did not consider satellite-specific effects such as the beam-width and stationspecific limitations such as slew rates at this point. It has to be mentioned that this type of study has been done for individual stations and not for baselines, i.e., station-dependent visibilities and not visibilities in the VLBI sense were analyzed.

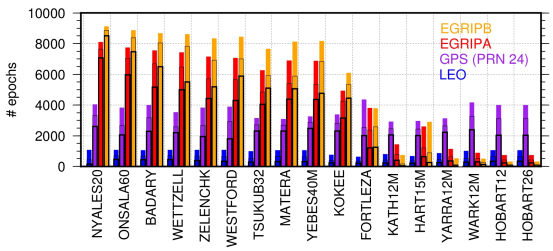



**Fig. 3** Number of epochs per week (January 4 – January 10, 2015) with spacecraft above horizon (cutoff elevation resp.); the column order is LEO (a=2000 km), GPS, E-GRIP-A, EGRIP-B; border line represents cutoff elevation: no border = 0°, normal border = 10°, and thick border = 20°; the stations are sorted in accordance to their latitude.

From the simulated observations we generated weekly solutions while estimating station coordinates, receiver clocks, and tropospheric zenith delays. The datum was defined by an NNT and NNR condition. The individual coordinate solutions $x_i$ were then compared by computing their repeatability, i.e., comparing the weekly solution against a combined long-term solution $x_m$. The repeatabilities are obtained for the north (n), east (e), and height (h) component by using the formula

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - x_m)^2)} \quad \text{with} \quad x \in \{n, e, h\}. \quad (1)$$

Figure 4 shows the derived station coordinate repeatabilities for the network EUROPE including the number of simulated observations per station. We use the term observation in this context as one satellite observation; thus the number of baseline observations is much higher. Obviously, the number of observations depends on the station latitude. In accordance with Figure 3, a difference of about 300 observations per day (corresponding to 30% of the total amount) can be found for the European network. The derived repeatabilities are in the range of 10 mm for all EUROPE stations. There is no latitudinal dependence of the repeatabilities visible in the EGRIP-A case. For EGRIP-B increased repeatabilities were found for stations situated in the South. In that case the 3D-repeatabilities reach 20 mm. The results are much more inhomogeneous for the GLOBAL network. As shown in Figure 4, comparable results can be derived in the EGRIP-A case for stations in the northern hemisphere (10 to 20 mm). However, due to the much lower number of observations in the southern hemisphere, the derived repeatabilities for such stations are incredibly large. In the case of EGRIP-B, similar results were found with slightly larger 3D-repeatabilities in the northern hemisphere (up to 30 mm); for some stations in the southern hemisphere, station coordinates could not be obtained due to missing observations.

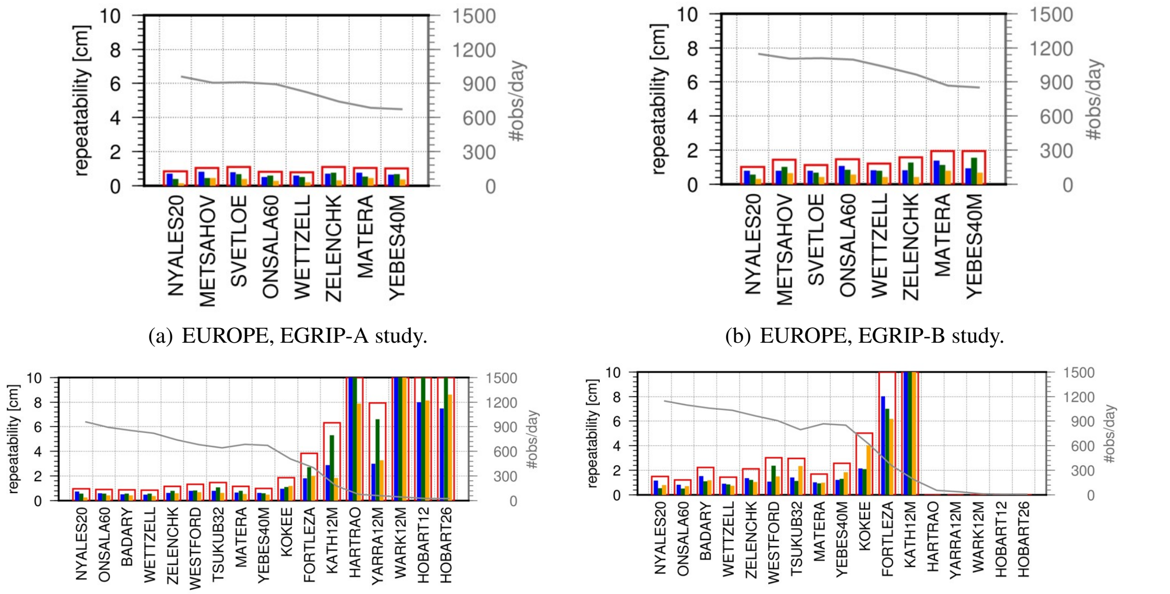
Comparing the derived repeatabilities against related simulation studies for LEO and GNSS satellites, values similar to the achieved results can be found for the EUROPE and northern GLOBAL stations (e.g., Plank et al., 2014).

## 4 Conclusions

We presented the new satellite mission E-GRIP aiming for tests of general relativity and co-location in space. Based on visibility simulation studies we showed the good observation conditions for VLBI satellite tracking, especially in the apogee region. Based on weekly solutions, we discussed the potential advantages for the obtained station coordinates when observing E-GRIP or other highly elliptical satellite orbits. Reaching repeatabilities comparable to LEO or GNSS orbits (i.e., 1–2 cm), also very long VLBI baselines are observable in a single-satellite tracking mode. However, the considered extreme eccentricities ($e > 0.6$) might be ideal for relativity tests but too large for a pure co-location mission as we could not derive coordinates for several stations in southern regions due to the very low number of observations associated with the perigee region.

## References

Bar-Sever, Y. E., Haines, B., Wu, S., Lemoine, F., and Willis, P. (2009). Geodetic Reference Antenna in Space (GRASP): A Mission to Enhance the Terrestrial Reference Frame. In *COSPAR colloquium: scientific and fundamental aspects of the Galileo program*. Padua, 2009.




(a) EUROPE, EGRIP-A study. (b) EUROPE, EGRIP-B study.

(c) GLOBAL, EGRIP-A study. (d) GLOBAL, EGRIP-B study.

**Fig. 4** Station coordinate repeatabilities; the column order is north, east, up with 3D encasing bar. The stations are sorted in accordance to their latitude; average number of daily observations.

Böhm, J., Wresnik, J., and Pany, A. (2006). Simulation of wet zenith delays and clocks. IVS Memorandum 2006-013v03.

Haas, R., Neidhardt, A., Kodet, J., Plötz, C., Schreiber, U., Kronschnabl, G., Pogrebenko, S., Duev, D., Casey, S., Marti-Vidal, I., Yang, J., and Plank, L. (2014). The Wettzell-Onsala G130128 Experiment - VLBI observations of a GLONASS satellite. In Behrend, D., Baver, K., and Armstrong, K., editors, *IVS 2014 General Meeting Proceedings*, pages 451–455. Science Press (Beijing), ISBN 978-7-03-042974-2.

Kodet, J., Schreiber, U., Plötz, C., Neidhardt, A., Kronschnabl, G., Haas, R., Calvès, G. M., Pogrebenko, S., Rothacher, M., Männel, B., Plank, L., and Hellerschmied, A. (2014). Co-locations of Space Geodetic Techniques on Ground and in Space. In Behrend, D., Baver, K., and Armstrong, K., editors, *IVS 2014 General Meeting Proceedings*, pages 446–450. Science Press (Beijing), ISBN 978-7-03-042974-2.

Männel, B., Rothacher, M., Kodet, J., Schreiber, U., and Schmid, R. (2014). GLONASS Satellites Simultaneously Observed by VLBI, GNSS and SLR. In Behrend, D., Baver, K., and Armstrong, K., editors, *IVS 2014 General Meeting Proceedings*, pages 461–465. Science Press (Beijing), ISBN 978-7-03-042974-2.

Plank, L., Böhm, J., and Schuh, H. (2014). Precise station positions from VLBI observations to satellites: a simulation study. *J Geod*, 88:1–15.

Tornatore, V. and Haas, R. (2009). Considerations on the observation of GNSS-signals with the VLBI2010 system. In *Proceedings of the 19th European VLBI for Geodesy and Astrometry Working Meeting*.

Tornatore, V., Haas, R., Duev, D., Pogrebenko, S., Casey, S., and Calvés, G. M. (2014). Direct VLBI Observations of GLobal Navigation Satellite System Signals. In Rizos, C. and Willis, P., editors, *Earth on the Edge: Science of a Sustainable Planet*. doi:10.1007/978-3-642-37222-3_32.